Flavor-changing top quark decays in *R*-parity-violating supersymmetric models

Jin Min Yang,[1,2,*] Bing-Lin Young,[1] and X. Zhang[3,4]
[1]*Department of Physics and Astronomy, Iowa State University, Ames, Iowa 50011*
[2]*International Institute of Theoretical and Applied Physics, Iowa State University, Ames, Iowa 50011*
[3]*CCAST (World Laboratory), P.O. Box 8730, Beijing 100080, China*
[4]*Institute of High Energy Physics, Academia Sinica, Beijing 100039, China*
(Received 16 June 1997; published 15 July 1998)

The flavor-changing top quark decays $t\to cV$ $(V=Z,\gamma,g)$ induced by *R*-parity-violating couplings in the minimal supersymmetric standard model are evaluated. We find that the decays $t\to cV$ can be significantly enhanced relative to those in the *R*-parity-conserving supersymmetric model. Our results show that the top quark flavor-changing neutral current decay can be as large as $\mathrm{Br}(t\to cg)\sim 10^{-3}$, $\mathrm{Br}(t\to cZ)\sim 10^{-4}$, and $\mathrm{Br}(t\to c\gamma)\sim 10^{-5}$, which may be observable at the upgraded Fermilab Tevatron and/or the CERN LHC. [S0556-2821(98)07315-9]

PACS number(s): 12.60.Jv, 11.30.Hv

The unexpected large mass of the top quark suggests that it may be more sensitive to new physics than other fermions. In the standard model (SM) the flavor-changing neutral current (FCNC) decays of the top quark $t\to cV$ suppressed by the Glashow-Iliopoulos-Maiani (GIM) mechanism, are found to be far below the detectable level [1,2]. So, searching for FCNC top-quark decays serves as a powerful probe to effects of new physics. The CDF [3,4] and D0 [5] Collaborations have reported interesting bounds on these decays [4]. Undoubtedly more stringent bounds will be obtained in the future at the Tevatron upgrade and the LHC.

A systematic theoretical study of the experimental observability for FCNC top-quark decays at the Tevatron and the LHC has been made in Refs. [6,7]. The results show that the detection sensitivity can be significant [6,7]:

$$\mathrm{Br}(t\to cZ)\simeq 4\times 10^{-3}(6\times 10^{-4}), \quad (1)$$

$$\mathrm{Br}(t\to c\gamma)\simeq 4\times 10^{-4}(8\times 10^{-5}), \quad (2)$$

$$\mathrm{Br}(t\to cg)\simeq 5\times 10^{-3}(1\times 10^{-3}), \quad (3)$$

at the upgraded Tevatron of integrated luminosity of 10 (100) fb^{-1}. The two electroweak modes can be improved severalfold at the LHC with similar integrated luminosities:

$$\mathrm{Br}(t\to cZ)\simeq 8\times 10^{-4}(2\times 10^{-4}), \quad (4)$$

$$\mathrm{Br}(t\to c\gamma)\simeq 2\times 10^{-5}(5\times 10^{-6}). \quad (5)$$

Despite the above interesting experimental possibilities, there is no demonstration in the minimal supersymmetric standard model (MSSM), which is the most favored candidate for physics beyond the standard model, that such limits can be realized. In MSSM conserving *R*-parity, the predictions for branching ratios of these FCNC top-quark decays were found to be significantly below the above detectable levels [8]. In this paper we will show that in the case of the *R*-parity violating MSSM [9,10] with the existing bounds on the *R*-parity violating couplings that violate the baryon number, $\mathrm{Br}(t\to cV)$ might reach the detectable level at the upgraded Tevatron and the LHC. However, as shown below, the effects of the lepton-number-violating λ' couplings in FCNC top-quark decays are negligibly small under the current constraints.

In the MSSM the superpotential with *R*-parity violation is given by [10]

$$\mathcal{W}_{\not R}=\lambda_{ijk}L_iL_jE_k^c+\lambda'_{ijk}L_iQ_jD_k^c +\lambda''_{ijk}\epsilon^{abd}U_{ia}^cD_{jb}^cD_{kd}^c+\mu_iL_iH_2, \quad (6)$$

where $L_i(Q_i)$ and $E_i(U_i,D_i)$ are the left-handed lepton (quark) doublet and right-handed lepton (quark) singlet chiral superfields. i,j,k are generation indices and c denotes charge conjugation. a, b, and d are the color indices and ϵ^{abd} is the total antisymmetric tensor. $H_{1,2}$ are the Higgs-doublets chiral superfields. The λ_{ijk} and λ'_{ijk} are lepton-number-violating ($\not L$) couplings and λ''_{ijk} baryon-number-violating ($\not B$) couplings. Constraints on these couplings have been obtained from various low-energy processes [11–20] and their phenomenologies at hadron and lepton colliders have also been investigated recently by a number of authors [19,21].

Although it is theoretically possible to have both $\not B$ and $\not L$ interactions, the nonobservation of proton decay prohibits their simultaneous presence [14]. We therefore assume the existence of either $\not L$ or $\not B$ couplings, and investigate their separate effects in top-quark decays.

The FCNC decays $t\to cV$ can be induced by either the λ' or λ'' coupling at the one loop level. In terms of the four-component Dirac notation, the Lagrangian of the $\not L$ couplings λ' and $\not B$ couplings λ'' are given by

$$\mathcal{L}_{\lambda'}=-\lambda'_{ijk}[\tilde{\nu}_L^i\overline{d}_R^kd_L^j+\tilde{d}_L^j\overline{d}_R^k\nu_L^i+(\tilde{d}_R^k)^*(\overline{\nu_L^i})^cd_L^j -\tilde{e}_L^i\overline{d}_R^ku_L^j-\tilde{u}_L^j\overline{d}_R^ke_L^i-(\tilde{d}_R^k)^*(\overline{e_L^i})^cu_L^j]+\mathrm{H.c.}, \quad (7)$$

*On leave from Department of Physics, Henan Normal University, China. Present address: Department of Physics, Tohoku University, Sendai 980-77, Japan.

$$\mathcal{L}_{\lambda''}=-\lambda''_{ijk}[\tilde{d}^k_R(\overline{u^i_L})^c d^j_L+\tilde{d}^j_R(\overline{d^k_L})^c u^i_L+\tilde{u}^i_R(\overline{d^j_L})^c d^k_L]+\text{H.c.}, \quad (8)$$

where the color indices in $\mathcal{L}_{\lambda''}$ are totally antisymmetric as in Eq. (6).

Let us first consider $t\to cV$ induced by $\not{L}$ couplings. At one-loop level, they give rise to effective tcV vertices of the form

$$V^\mu(tcZ)=ie[\gamma^\mu P_L A^Z+ik_\nu\sigma^{\mu\nu}P_R B^Z], \quad (9)$$

$$V^\mu(tc\gamma)=ie[ik_\nu\sigma^{\mu\nu}P_R B^\gamma], \quad (10)$$

$$V^\mu(tcg)=ig_s T^a[ik_\nu\sigma^{\mu\nu}P_R B^g], \quad (11)$$

where $P_{R,L}=\frac{1}{2}(1\pm\gamma_5)$ and k is the momentum of the vector boson. The form factors A^Z, B^Z, etc., are obtained by identifying $A^Z=A^Z_1+A^Z_2$ and $B^V=B^V_1+B^V_2$ $(V=Z,\gamma,g)$, where

$$A^Z_1=\frac{1}{16\pi^2}\lambda'_{i2k}\lambda'_{i3k}\Big\{(v_c+a_c)B_1(M_t,M_{e^i},M_{\tilde{d}^k}) -(v_e+a_e)\Big[2c_{24}-\frac{1}{2}+M_Z^2(c_{12}+c_{23})\Big](-p_t,p_c,M_{e^i},M_{\tilde{d}^k},M_{e^i}) +\xi_V[2c_{24}+M_t^2(c_{11}-c_{12}+c_{21}-c_{23})](-p_t,k,M_{e^i},M_{\tilde{d}^k},M_{\tilde{d}^k})\Big\}, \quad (12)$$

$$B^Z_1=\frac{1}{16\pi^2}\lambda'_{i2k}\lambda'_{i3k}\{(v_e+a_e)M_t[c_{11}-c_{12}+c_{21}-c_{23}](-p_t,p_c,M_{e^i},M_{\tilde{d}^k},M_{e^i}) +\xi_V M_t[c_{11}-c_{12}+c_{21}-c_{23}](-p_t,k,M_{e^i},M_{\tilde{d}^k},M_{\tilde{d}^k})\}, \quad (13)$$

$$A^Z_2=\frac{1}{16\pi^2}\lambda'_{i2k}\lambda'_{i3k}\Big\{(v_c+a_c)B_1(M_t,M_{d^k},M_{\tilde{e}^i}) -(a_d-v_d)\Big[2c_{24}-\frac{1}{2}+M_Z^2(c_{12}+c_{23})\Big](-p_t,p_c,M_{d^k},M_{\tilde{e}^i},M_{d^k}) -\xi'_V[2c_{24}+M_t^2(c_{11}-c_{12}+c_{21}-c_{23})](-p_t,k,M_{d^k},M_{\tilde{e}^i},M_{\tilde{e}^i})\Big\}, \quad (14)$$

$$B^Z_2=\frac{1}{16\pi^2}\lambda'_{i2k}\lambda'_{i3k}\{(a_d-v_d)M_t[c_{11}-c_{12}+c_{21}-c_{23}](-p_t,p_c,M_{d^k},M_{\tilde{e}^i},M_{d^k}) -\xi'_V M_t[c_{11}-c_{12}+c_{21}-c_{23}](-p_t,k,M_{d^k},M_{\tilde{e}^i},M_{\tilde{e}^i})\}. \quad (15)$$

The sum over family indices $i,k=1,2,3$ is implied. p_t and p_c are the momenta of the top and charm quarks. The functions B_1 and c_{ij} are two- and three-point Feynman integrals given in Ref. [22], and their functional dependences are indicated in the bracket following them. The constant ξ_V $(\xi'_V)=-e_d s_W/c_W$ $[-(1-2s_W^2)/2s_W c_W]$, $e_d(-1)$, 1 (0) are for the Z boson, photon, and gluon, respectively; $v_f=(I_3^f-2e_f s_W^2)/2s_W c_W$ and $a_f=I_3^f/2s_W c_W$ are the vector and axial-vector couplings with e_f being the electric charge of the fermion f in unit of e, and $I_3^f=\pm 1/2$ the corresponding third components of the weak isospin. The form factors $B^\gamma_{1,2}$ and $B^g_{1,2}$ are obtained from $B^Z_{1,2}$ by the substitutions $B^\gamma_1=B^Z_1(a_e\to 0,v_e\to e_e)$, $B^\gamma_2=B^Z_2(a_d\to 0,v_d\to e_d)$, $B^g_1=B^Z_1(a_e\to 0,v_e\to 0)$, and $B^g_2=B^Z_2(a_d\to 0,v_d\to 1)$ and setting $M_Z\to 0$.

Note that the ultraviolet divergencies are contained in Feynman integrals B_1 and c_{24}. We have checked that all the ultraviolet divergencies cancelled as a result of the renormalizability of the MSSM.

Similarly, we have calculated the effective tcV vertices induced by the $\not{B}$ couplings at the one-loop level. The effective vertices have forms similar to those of Eqs. (9)–(11) with the substitutions $A^V\to F^V_1$, $B^V\to F^V_2$, where

$$F_1^Z=\frac{1}{16\pi^2}\lambda''_{2jk}\lambda''_{3jk}\Big\{(v_c+a_c)B_1(M_t,M_{d^j},M_{\tilde{d}^k}) +(v_d+a_d)\Big[\frac{1}{2}-2c_{24}-M_V^2(c_{12}+c_{23})\Big] \times(-p_t,p_c,M_{d^j},M_{\tilde{d}^k},M_{d^j}) -\xi_V[2c_{24}+M_t^2(c_{11}-c_{12}+c_{21}-c_{23})] \times(-p_t,k,M_{d^j},M_{\tilde{d}^k},M_{\tilde{d}^k})\Big\}, \quad (16)$$

$$F_2^Z=\frac{1}{16\pi^2}\lambda''_{2jk}\lambda''_{3jk}\{(v_d+a_d)M_t[c_{11}-c_{12}+c_{21}-c_{23}] \times(-p_t,p_c,M_{d^j},M_{\tilde{d}^k},M_{d^j})-\xi_V M_t \times[c_{11}-c_{12}+c_{21}-c_{23}] \times(-p_t,k,M_{d^j},M_{\tilde{d}^k},M_{\tilde{d}^k})\}, \quad (17)$$

$$F_2^\gamma=F_2^Z|_{a_d\to 0,v_d\to e_d}, \quad F_2^g=F_2^Z|_{a_d\to 0,v_d\to -1,\xi_V\to -\xi_V}. \quad (18)$$

The sum over family indices $j,k=1,2,3$ is implied.

Now we present the numerical results for $\mathrm{Br}(t\to cV)$. We take $M_t=175$ GeV, $m_Z=91.187$ GeV, $m_W=80.3$ GeV, $G_F=1.16639\times10^{-5}(\mathrm{GeV})^{-2}$, $\alpha=1/128$, $\alpha_s=0.108$, and neglect the masses of charged leptons, down-type quarks, and the charm quark. The decay rates increase with the relevant λ' or λ'' couplings and decrease with the increase of the sparticle mass.

We note that there are two mass eigenstates for each flavor squark and slepton, and the nonzero off-diagonal terms in the fermion mass matrix will induce the mass splitting between the two mass eigenstates [23]. Since the off-diagonal terms in the mass matrix are proportional to the mass of the corresponding fermion [23], the off-diagonal terms in the mass matrix of the down-type squark and the slepton are relatively small. For simplicity, we assumed all the down-type squark masses to be degenerate, as well as the masses of the sleptons. As we shall discuss later, these technical assumptions do not affect our results.

L-violating couplings. To calculate the bounds of the $\mathrm{Br}(t\to cV)$ in the presence of the $\not{L}$ terms, we use the following limits on the $\not{L}$ couplings (obtained for the squark mass of 100 GeV): $|\lambda'_{kij}|<0.012$ $(k,j=1,2,3;i=2)$ [16], $|\lambda'_{13j}|<0.16$ $(j=1,2)$ [18], $|\lambda'_{133}|<0.001$ [15], $|\lambda'_{23j}|<0.16$ $(j=1,2,3)$, and $|\lambda'_{33j}|<0.26$ $(j=1,2,3)$ [19]. There are also the following constraints on the products of the λ' couplings [17,18]: $\lambda'_{13i}\lambda'_{12i}$, $\lambda'_{23j}\lambda'_{22j}<1.1\times10^{-3}$ $(i=1,2;j=1,2,3)$, $\lambda'_{in2}\lambda'_{jn1}<10^{-5}(i,j,n=1,2,3)$, and $\lambda'_{121}\lambda'_{222}$, $\lambda'_{122}\lambda'_{221}$, $\lambda'_{131}\lambda'_{232}$, $\lambda'_{132}\lambda'_{231}<10^{-7}$.

Using the upper limits of the relevant $\not{L}$ couplings and taking the lower limit of 45 GeV for slepton mass, we find the maximum values of the branching fractions to be

$$\mathrm{Br}(t\to cZ)\leqslant10^{-9}, \quad \mathrm{Br}(t\to c\gamma)\leqslant10^{-10},$$

$$\mathrm{Br}(t\to cg)\leqslant10^{-8}. \quad (19)$$

If we consider the mass splitting between sleptons, these upper limits on the branching fractions still persist. Thus we conclude that the contributions of the $\not{L}$ couplings to $t\to cV$ are too small to be of interest.

B-violating couplings. For the $\not{B}$ couplings λ'' the bound on the top-quark rare decay rates can be significantly increased since the λ'' couplings stand relatively unconstrained, except for λ''_{112} and λ''_{113} which have been strongly bounded from the consideration of double nucleon decay into two kaons [12] and an n-$\bar{n}$ oscillation [12], respectively.

Under the assumption that the masses of all down-type squarks are degenerate, $\mathrm{Br}(t\to cV)$ is proportional to Λ^2 with Λ being the product of the relevant $\not{B}$ couplings defined by

$$\Lambda\equiv\lambda''_{212}\lambda''_{312}+\lambda''_{213}\lambda''_{313}+\lambda''_{223}\lambda''_{323}=\frac{1}{2}\lambda''_{2jk}\lambda''_{3jk}. \quad (20)$$

While the experimental bounds on λ''_{3jk} have been derived from the ratio of hadron to lepton width of the Z^0, $R_l\equiv\Gamma_h/\Gamma_l$ [20], we are not aware of any experimental bounds on λ''_{2jk} although one can make general estimates from certain low-energy data. Therefore, we do not have an experimental bound for Λ. We discuss these points in some detail below.

First we will argue that it is likly that only one term in Λ, Eq. (20), can be significant. This comes from the consideration of the low-energy processes $b\to s\gamma$ and K^0-$\bar{K}^0$ mixing. This may provide strong constraints to the products $\lambda''_{i12}\lambda''_{i13}$ and $\lambda''_{i13}\lambda''_{i23}$ (sum over i is implied), respectively [24]. Thus the simultaneous presence of any two terms in Λ might conflict with these low-energy processes. However, the existence of only one of the terms, $\lambda''_{212}\lambda''_{312}$, $\lambda''_{213}\lambda''_{313}$, or $\lambda''_{223}\lambda''_{323}$, will not be constrained by them.

The bound on λ''_{3jk} from $R_l\equiv\Gamma_h/\Gamma_l$ is 1.46 at 2σ for down squark mass of 100 GeV [20]. We can obtain another constraint from the FNAL data of $t\bar{t}$ events by examining the exotic top-quark decay $t\to\overline{d_L^j}+\bar{\tilde{d}}_R^k$. For the top-quark mass of 175 GeV, we have

$$R_t\equiv\frac{\Gamma(t\to\overline{d_L^j}+\bar{\tilde{d}}_R^k)}{\Gamma(t\to W+b)}=1.12(\lambda''_{3jk})^2\left[1-\left(\frac{M_{\tilde{d}_R^k}}{175\ \mathrm{GeV}}\right)^2\right]^2 \times\theta\left(1-\frac{m_{\tilde{d}}}{m_t}\right). \quad (21)$$

The $\tilde{d}_R^k$ can decay into a d_R plus a lightest neutralino (and gluino if kinematically allowed), as well as quark pairs induced by the $\not{B}$ terms. The decay modes $t\to\overline{d_L^j}+\bar{\tilde{d}}_R^k$ can enhance the total fraction of hadronic decays of the top quark and alter the ratio of $t\bar{t}$ events expected in the dilepton channel. The number of dilepton events expected in the presence of the decay $t\to\overline{d_L^j}+\bar{\tilde{d}}_R^k$ and that in the SM is given by $R(f)\equiv(1-f)^2$, where $f=\mathrm{Br}(t\to\overline{d_L^j}+\bar{\tilde{d}}_R^k)$. The CDF mea-

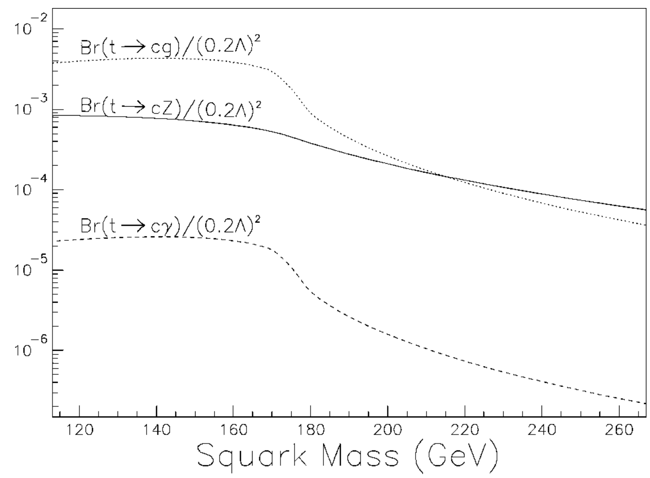

FIG. 1. The plot of $\mathrm{Br}(t\to cV)/(0.2\Lambda)^2$ as a function of squark mass.

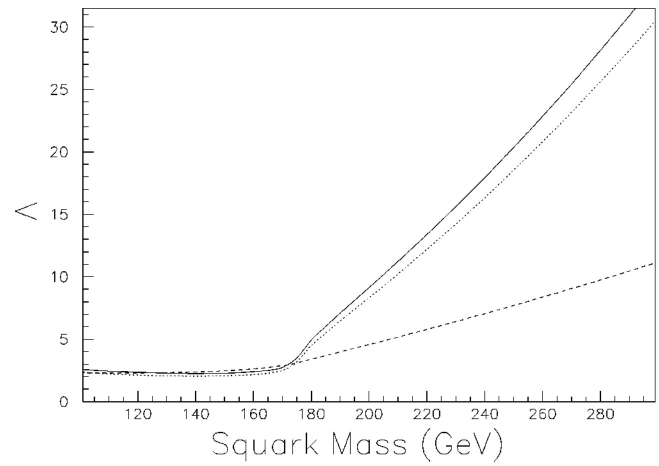

FIG. 2. Λ versus squark mass for given values of branching ratios. The solid, dashed, and dotted lines correspond to $\mathrm{Br}(t\to cg)=1\times10^{-3}$, $\mathrm{Br}(t\to cZ)=2\times10^{-4}$, and $\mathrm{Br}(t\to c\gamma)=5\times10^{-6}$, respectively.

surement of the $t\bar{t}$ production cross section is $\sigma[t\bar{t}]_{\rm exp}=8.3^{+4.3}_{-3.3}$ pb in the dilepton channel [25], while the SM expectation for a top-quark mass of 175 GeV is $\sigma[t\bar{t}]_{\rm QCD}=5.5^{+0.1}_{-0.4}$ pb [26]. By requiring $R(f)$ to lie within the measured range of $\sigma[t\bar{t}]_{\rm exp}/\sigma[t\bar{t}]_{\rm QCD}$, we can obtain the bounds on the relevant λ'' couplings. The 2σ bound from dilepton channel is found to be

$$(\lambda''_{3jk})^2\left[1-\left(\frac{M_{\tilde{d}^k_R}}{175\ \ \mathrm{GeV}}\right)^2\right]^2<0.71. \tag{22}$$

For $M_{\tilde{d}^k_R}=100$ GeV, we have $\lambda''_{3jk}<1.25$, comparable to the bound from R_l [20]. Constraints on λ''_{3jk} from the experimental data of $t\bar{t}$ in other channels are weaker.

Although we are not aware of any experimental bound for λ''_{2jk}, theoretical bounds can be derived under specific assumptions [11]. The constraint of perturbative unitarity at the SUSY breaking scale $M_{\rm SUSY}$ would bound all the couplings, and in particular $(\lambda''_{2jk})^2/4\pi<1$, i.e., $\lambda''_{2jk}<3.54$. A stronger bound can be obtained if we assume gauge group unification at $M_U=2\times10^{16}$ GeV and the Yukawa couplings Y_t, Y_b, and Y_τ to remain in the perturbative domain in the whole range up to M_U. This implies $Y_i(\mu)<1$ for $\mu<2\times10^{16}$ GeV. Then we obtain an upper bound of 0.6 for all λ''_{ijk} [11]. In this latter case, if all the terms in Λ exist and take their maximum value of 0.6, then Λ is at most of the order of 1. But there is no *a priori* reason to take this theoretical assumption. Taking the former scenario of perturbative unitarity at the SUSY breaking scale and letting, for example, λ''_{212} and λ''_{312} have their maximal allowed values and taking all the other λ'''s to be small, then we have Λ as large as 5, which would make the top-quark neutral current decays observable as our results below show.

Now we present the numerical results for the effects of λ'' couplings by considering Λ as a variable and dividing it out from the branching ratios. In Fig. 1 we present the plot of $\mathrm{Br}(t\to cV)/(0.2\Lambda)^2$ as a function of squark mass. For a squark mass no greater than 170 GeV we have

$$\mathrm{Br}(t\to cZ)\approx(0.6\Lambda)^2\times10^{-4}, \tag{23}$$

$$\mathrm{Br}(t\to c\gamma)\approx(0.3\Lambda)^2\times10^{-5}, \tag{24}$$

$$\mathrm{Br}(t\to cg)\approx(0.4\Lambda)^2\times10^{-3}. \tag{25}$$

We conclude from Eqs. (23)–(25), Eqs. (1)–(5), and a Λ as large as 5 that the contribution of $\not{B}$ couplings to the decay $t\to cV$ might be observable at the upgraded Tevatron and LHC.

If the decays $t\to cV$ are not observed at the upgraded Tevatron and LHC, we can obtain the experimental upper bound for Λ. We illustrate this in Fig. 2 where we plot Λ versus the degenerate squark mass. The solid, dashed, and dotted lines correspond to $\mathrm{Br}(t\to cg)=1\times10^{-3}$, $\mathrm{Br}(t\to cZ)=2\times10^{-4}$, and $\mathrm{Br}(t\to c\gamma)=5\times10^{-6}$, respectively. The region above the solid line corresponding to $\mathrm{Br}(t\to cg)>1\times10^{-3}$ will be excluded if the decay $t\to cg$ is not observed at the upgraded Tevatron. The region above the dashed and dotted lines corresponds to $\mathrm{Br}(t\to cZ)>2\times10^{-4}$ and $\mathrm{Br}(t\to c\gamma)>5\times10^{-6}$ which will be excluded if corresponding decays are not observed at the LHC. The corresponding value of Λ which sets its upper bound can be read off from the figure. For example, for a squark mass of 150 GeV, the upgraded Tevatron can probe the Λ down to 2.3. This bound is not very strong but may serve as the first experimental bound on this hitherto experimentally unconstrained product of λ'' couplings.

The following remarks are due regarding the above results.

(a) For the upgraded Tevatron or LHC, the limits on some individual or combinations of these couplings may be obtainable from direct squark search. However, we think that our results are complementary to the direct search and the processes discussed in the present article may involve different combination of the couplings. Since the *R*-violating SUSY contains many parameters, it is desirable to obtain as many constraints as possible.

(b) If the HERA anomalous events [27] were the result of *R*-parity-violating terms [28], namely, nonzero values for $\not{L}$ couplings λ', all the $\not{B}$ couplings λ'' would be very small since proton stability imposes a upper bound of $10^{-9}(10^{-11})$ for any products of $\lambda'\lambda''$ in the absence (presence) of squark flavor mixing [14]. Then the effects of any λ'' coupling would, of course, not be observable.

(c) As we have pointed out, only one term in Λ can exist, either $\lambda''_{212}\lambda''_{312}$, $\lambda''_{213}\lambda''_{313}$, or $\lambda''_{223}\lambda''_{323}$. Let us assume the existence of $\lambda''_{212}\lambda''_{312}$ as an example. Besides the two-body rare decays $t\to cV$, the three-body decays $t\to cd\bar{d}$ (exchanging a $\tilde{s}$) and $t\to cs\bar{s}$ (exchanging a $\tilde{d}$) can also open. Although these decay modes just give rise to three light jets and thus are not easy to detect at the upgraded Tevatron or LHC, a detailed examination for the possibility of detecting these decay modes is needed [24].

(d) In the contributions of λ'' couplings, the masses of down-type squarks $\tilde{d}$, $\tilde{s}$, and $\tilde{b}$ are involved. In our calculation, we assumed the degeneracy of these masses so that we extracted a factor Λ in Eq. (20). However, as we have pointed out, only one term in Λ can exist. Correspondingly, only one flavor of down-type squark is involved. So actually our assumption of mass degeneracy between different flavor down-type squarks does not affect our numerical results.

Further, we assumed the mass degeneracy between the two mass eigenstates for each flavor down-type squark. Again, let us assume the existence of the term $\lambda''_{212}\lambda''_{312}$ as an example. Then only the strange squark ($\tilde{s}$) is involved. There are two mass eigenstates for it, namely, $\tilde{s}_1$ and $\tilde{s}_2$. We assumed $m_{\tilde{s}_1}=m_{\tilde{s}_2}$ in our calculation. Theoretically this is a good approximation because the mass splitting between $\tilde{s}_1$ and $\tilde{s}_2$ is proportional to the strange-quark mass [23]. We also checked that our numerical results are not sensitive to the small mass splitting.

Although the possible mass splittings between different flavor squarks cannot significantly enhance the rates of top-quark rare decays, they would cause some unexpected effects in low-energy processes. For example, the large mass splitting between charm squark and up squark, which are not relevant to our calculations in this paper, would lead to large FCNC processes in the *D*-meson system. This will be examined in detail in our future work.

(e) Finally, we should point out that with couplings as large as 3.5, the model cannot be extrapolated beyond a few TeV, which will take away many of the motivations of supersymmetry.

In summary, we found that the decays $t\to cV$ can be significantly enhanced relative to those in the *R*-parity-conserving SUSY model. In an optimistic scenario where one of the products of Λ in Eq. (20) attend the allowed limit by perturbative unitarity at the SUSY breaking scale and by R_l, the branching ratios can be as large as $\mathrm{Br}(t\to cg)\sim10^{-3}$, $\mathrm{Br}(t\to cZ)\sim10^{-4}$, and $\mathrm{Br}(t\to c\gamma)\sim10^{-5}$, which are potentially observable at the upgraded Tevatron and/or the LHC. If not seen, upper bounds can be set on the specific combination of the relevant $\not{B}$ couplings. Together with low-energy processes such as $b\to s\gamma$ and $K^0-\bar{K}^0$ mixing, strong bounds on most of the λ'' couplings can be set.

We thank A. Datta, T. Han, and C. Kao for discussions. This work was supported in part by the U.S. Department of Energy, Division of High Energy Physics, under Grant Nos. DE-FG02-94ER40817 and DE-FG02-92ER40730. X.Z. was also supported in part by National Natural Science Foundation of China and J.M.Y. acknowledge the partial support provided by the Henan Distinguished Young Scholars Fund.

[1] J. L. Diaz-Cruz *et al.*, Phys. Rev. D **41**, 891 (1990); B. Dutta Roy *et al.*, Phys. Rev. Lett. **65**, 827 (1990); H. Fritzsch, Phys. Lett. B **224**, 423 (1989); W. Buchmuller and M. Gronau, *ibid.* **220**, 641 (1989).
[2] G. Eilam, J. L. Hewett, and A. Soni, Phys. Rev. D **44**, 1473 (1991).
[3] J. Incandela (CDF), Report No. FERMILAB-CONF-95/237-E, 1995 (unpublished); D. Gerdes,hep-ex/9706001.
[4] T. J. Lecompte (CDF), Report No. FERMILAB-CONF-96/021-E, 1996 (unpublished).
[5] A. P. Heinson (DO), hep-ex/9605010.
[6] T. Han, R. D. Peccei, and X. Zhang, Nucl. Phys. **B454**, 527 (1995); T. Han, K. Whisnant, B.-L. Young, and X. Zhang, Phys. Rev. D **55**, 7241 (1997); Phys. Lett. B **385**, 311 (1996); A. Heison, Report No. FERMILAB-CONF-96/116-E, 1996 (unpublished).
[7] T. Tait and C.-P. Yuan, Phys. Rev. D **55**, 7300 (1997); E. Malkawi and T. Tait, *ibid.* **54**, 5758 (1996); M. Hosch, K. Whisnant, and B.-L. Young, *ibid.* **56**, 5725 (1997); TeV 2000 working group, Report No. FERMILAB-PUB-96/082, edited by D. Amidei and R. Brock (unpublished).
[8] C. S. Li, R. J. Oakes, and J. M. Yang, Phys. Rev. D **49**, 293 (1994); J. M. Yang and C. S. Li, *ibid.* **49**, 3412 (1994); G. Couture, C. Hamzaoui, and H. Konig, *ibid.* **52**, 1713 (1995); J. L. Lopez, D. V. Nanopoulos, and R. Rangarajan, *ibid.* **56**, 3100 (1997); G. Couture, M. Frank, and H. Konig, *ibid.* **56**, 4213 (1997); G. M. de Divitiis, R. Petronzio, and L. Silvestrini, Nucl. Phys. **B504**, 45 (1997).
[9] For reviews of the MSSM, see, for example, H. E. Haber and G. L. Kane, Phys. Rep. **117**, 75 (1985); J. F. Gunion and H. E. Haber, Nucl. Phys. **B272**, 1 (1986).
[10] For reviews of *R*-parity-violating couplings, see, for example, D. P. Roy, hep-ph/9303324; G. Bhattacharyya, Nucl. Phys. B (Proc. Suppl.) **52**, 83 (1997).
[11] B. Brahmachari and P. Roy, Phys. Rev. D **50**, 39 (1994).
[12] J. L. Goity and M. Sher, Phys. Lett. B **346**, 69 (1995).
[13] R. N. Mohapatra, Phys. Rev. D **34**, 3457 (1986); M. Hirsch, H. V. Klapdor-Kleingrothaus, and S. G. Kovalenko, Phys. Rev.

Lett. **75**, 17 (1995); K. S. Babu and R. N. Mohapatra, *ibid.* **75**, 2276 (1995); V. Barger, G. F. Giudice, and T. Han, Phys. Rev. D **40**, 2978 (1989); G. Bhattacharyya and D. Choudhury, Mod. Phys. Lett. A **10**, 1699 (1995); D. E. Kaplan, hep-ph/9703347; J. Jang, J. K. Kim, and J. S. Lee, Phys. Rev. D **55**, 7296 (1997).

[14] A.Y. Smirnov and F. Vissani, Phys. Lett. B **380**, 317 (1996); F. Zwirner, *ibid.* **132**, 103 (1983).

[15] S. Dimopoulos and L. J. Hall, Phys. Lett. B **207**, 210 (1987); R. M. Godbole, P. Roy, and X. Tata, Nucl. Phys. **B401**, 67 (1993).

[16] K. Agashe and M. Graesser, Phys. Rev. D **54**, 4445 (1996).

[17] D. Choudhury and P. Roy, Phys. Lett. B **378**, 153 (1996).

[18] J. Jang, J. K. Kim, and J. S. Lee, Phys. Lett. B **408**, 367 (1997).

[19] G. Bhattacharyya, J. Ellis, and K. Sridhar, Mod. Phys. Lett. A **10**, 1583 (1995).

[20] G. Bhattacharyya, D. Choudhury, and K. Sridhar, Phys. Lett. B **355**, 193 (1995).

[21] J. Erler, J. L. Feng, and N. Polonsky, Phys. Rev. Lett. **78**, 3063 (1997); D. K. Ghosh, S. Raychaudhuri, and K. Sridhar, Phys. Lett. B **396**, 177 (1997); D. Choudhury and S. Raychaudhuri, *ibid.* **401**, 54 (1997); A. Datta, J. M. Yang, B.-L. Young, and X. Zhang, Phys. Rev. D **56**, 3107 (1997).

[22] G. Passarino and M. Veltman, Nucl. Phys. **B160**, 151 (1979).

[23] J. Ellis and S. Rudaz, Phys. Lett. **128B**, 248 (1983); A. Bouquet, J. Kaplan, and C. Savoy, Nucl. Phys. **B262**, 299 (1985).

[24] J. M. Yang *et al.* (in progress).

[25] D. Gerdes, hep-ex/9609013.

[26] See, for example, E. L. Berger and H. Contopanagos, Phys. Lett. B **361**, 115 (1995).

[27] H1 Collaboration, C. Adloff *et al.*, Z. Phys. C **74**, 191 (1997); ZEUS Collaboration, J. Breitweg *et al.*, *ibid.* **74**, 207 (1997).

[28] D. Choudhury and S. Raychaudhuri, Phys. Lett. B **401**, 54 (1997); G. Altarelli, J. Ellis, G. F. Guidice, S. Lola, and M. L. Mangano, Nucl. Phys. **B506**, 3 (1997); H. Dreiner and P. Morawitz, *ibid.* **B503**, 55 (1997); J. Kalinowski, R. Rückl, H. Spiesberger, and P. M. Zerwas, Z. Phys. C **74**, 595 (1997).